



# ***Systems Engineering Lessons Learned from Solar Array Structures and Mechanisms Deployment***

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## ***Purpose and Agenda***

- Purpose:
  - The overall purpose of this presentation is to present a summary of System Engineering (SE) lessons learned from previous failures/anomalies of deployable solar array structures and mechanisms to help avoid repeating the past failures for future solar array system development programs.
  - This presentation is based on a prior Glenn Research Center (GRC) Solar Electric Propulsion Technology Demonstration report , " Lessons Learned Summary of Deployable Structures /Appendages and Mechanisms" done by Mr. Thomas Kraft of GRC and Mr. Vipavetz in 2012



## ***Agenda***

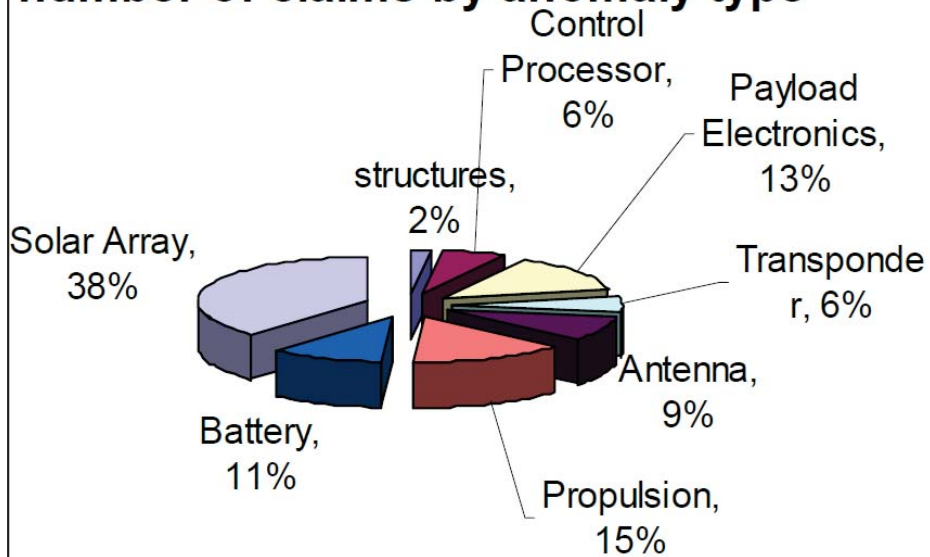
- Review of some failure history
  - Breakdown of failures by type of failure and cost of failure
- Review four (4) common causes for anomalies/failures
  - Focus on the SE causes
- Summary
  - Review key lessons learned/recommendations
- Key Solar Array Structure requirements



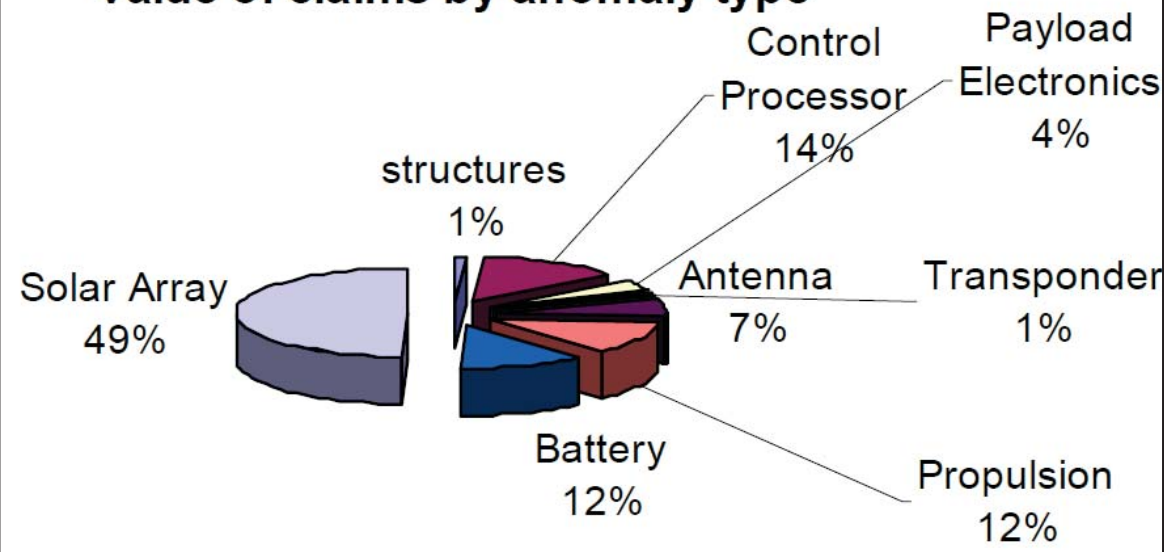
# Satellite Failure History

- Based on presentation at 2005 Space Power Workshop<sup>1</sup>, satellite reliability in orbit has been shown to be poor
  - Majority of claims coming from satellite bus – not from the launch vehicle
- Solar array failures are a high % of overall satellite insurance costs

**number of claims by anomaly type**



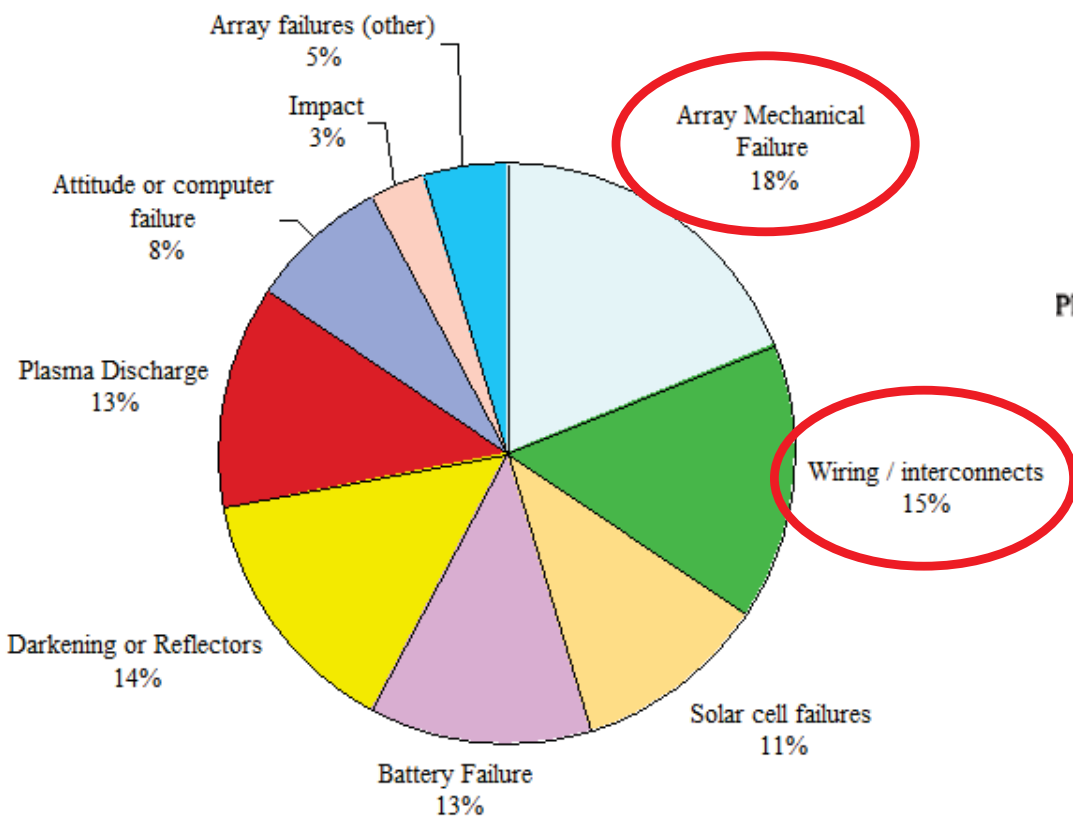
**value of claims by anomaly type**



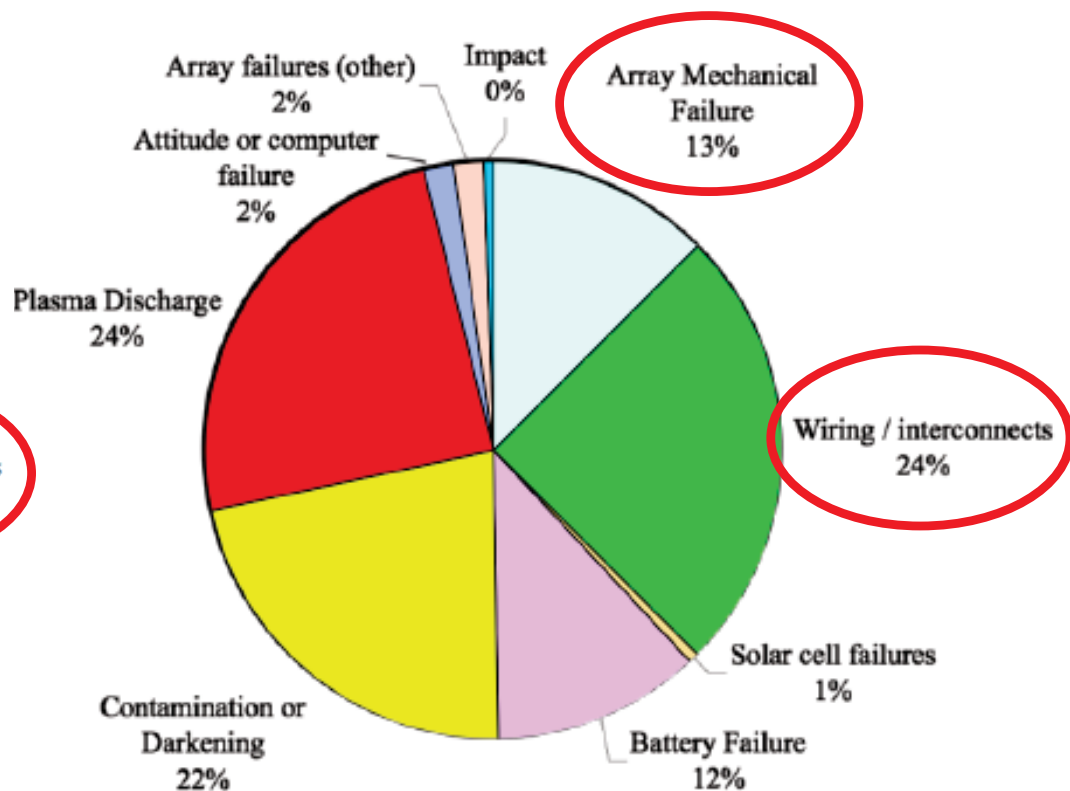


# Power System Related Anomaly History

- In a NASA GRC study on data obtained covering power failures of commercial and scientific satellites from 1990-2009 <sup>2</sup>, a high percentage of failures were associated with solar arrays mechanical failures and solar array wiring/interconnects



**% Power Failures – By Failure Type**



**Cost of Failure – By Failure Type**



# ***Leading Causes of Deployment Failures***

- There are many causes for failures of appendages, deployable structures and mechanisms, however these failures can be grouped into four general categories:
  1. Mechanical Loading
    - Ground transportation/launch/in-space loads
  2. On-orbit Space Environments
  3. Tribology (Mechanisms and Lubricants)
  4. Systems Engineering (**Focus**)
    - Requirements
    - Modeling/Analysis
    - Assembly, Integration and Testing



# ***Challenges Associated w/ Requirements and Modeling/Analysis***

**Many problems occur due to a breakdown in systems engineering, not a breakdown in individual core disciplines**

- Requirements: Specific challenges associated with requirements:
  - Poor requirements and verification management
  - Lack of highly skilled requirement writers
  - Poor requirements traceability and allocation
  - Poor configuration control of requirement changes and waivers
  - Lack of requirement ownership
- Modeling/Analysis:
  - Large flexible structures are often highly non-linear in nature
  - Difficult to accurately model/predict actual loads/environments



# ***Challenges Associated with Assembly, Integration & Testing (AI&T)***

- Common AI&T challenges associated with deployable structures/mechanisms:
  - The sheer size of solar array systems
  - Solar array workmanship issues
  - Size limitations of test facilities
  - Difficulty of representing the intended operating environment <sup>3</sup>
  - Gravity off-loader used for ground deployment testing and associated test equipment can mask small forces encountered during deployment testing
  - Difficulty of minimizing effects of instrumentation during ground testing
  - Difficulty of evaluating venting during ground testing <sup>3</sup>



# ***Non-Space Environment Requirement Lessons***

- (SE LL1) Handling and ground transportation requirements
  - Graphite/epoxy and Kevlar/epoxy structures can be easily damage
- (SE LL2) Launch mechanical load requirements
  - Large lightweight structures very susceptible
  - Wiring/interconnects/solder joints and switches are particularly susceptible
  - Items such as cables, tethers and insulation can move/shift unexpectedly during launch causing interference/jamming issues during operation/deployment
- (SE LL3) Pyrotechnic shock requirements
  - Pyrotechnic shock can produce significant irreversible loads to surrounding systems/components
  - Smaller mechanisms/components are more susceptible
  - Flying debris/premature firing are areas of concern
- (SE LL4) Plume loading requirements
  - Relatively small external loads, can vary dramatically as a function of thruster type, location, and operating conditions
  - Can have a substantial impact on spacecraft performance
  - Is growing contributor as the surface areas of arrays increase in size
- (SE LL5) Attitude control load requirements
  - Spacecraft structural dynamical interactions with this can be very subtle and complex



## ***Recommendations***

- (Recommendation SE1) Verify mechanical load margins are adequate “worst” case loadings
  - Use the largest possible margins of operation due to uncertainties in mechanical loads
  - Be especially sensitive to more fragile deployable structure sub-assemblies (solar cells, wiring/interconnects, solder joints and switches)
- (Recommendation SE2) Use a mechanical devices, such as pins, skewers, or interlocking sections to secure items such as cables, tethers and blankets (constraints on system)
- (Recommendation SE3 ) Verify deployable structures/mechanisms can withstand pyrotechnic shocks
  - Also consider protection from flying debris
- (Recommendation SE4 ) Identify externally induced in-space environments from your ConOps and incorporate into the system requirements
  - Special consideration should be given to plume loading due to its subtle but often complex nature
- (Recommendation SE5) Develop “Use Cases” based on ConOps scenarios to understand Attitude Control and their interactions.



# ***On-Orbit Space Environment Lessons***

- (SE LL6) Effects of hostile space environment (radiation, charging, arcing, heat dissipation, and microgravity)
  - Flexible solar arrays and mechanisms are particularly sensitive to the effects of space thermal, vacuum and “0-g” environments.
- (SE LL7) Situational Awareness of space environment and critical operations
  - Periodic environmental disturbances such as geomagnetic storms can trigger an electrostatic discharge event
  - Micrometeoroid storms have severely damaged spacecraft/structure
- (SE LL8) Dealing with the vacuum of space
  - Unvented honeycomb panels can entrap moisture and delaminate during ascent depressurization
  - Large lightweight structures especially vulnerable to venting issues



# ***On-Orbit Space Environments Recommendations***

- (Recommendation SE6) Be aware of all hostile environmental effects and apply system requirements for worst-case space environments, particularly to vacuum, thermal and “0-G” effects
  - Special attention:
    - » to differences in thermal expansion coefficients for deployable retention devices/release mechanisms.
    - » to thermal effects on wiring, interconnects and solder joints
    - » to thermal gradients in deployable structures/mechanisms
- (Recommendation SE7) Use the ConOps for advanced mission/operations planning
  - Account for known periodic environmental disturbances and events such as geomagnetic and micro-meteoroid storms
  - Incorporate real-time video (or similar device) to visually monitor operation of deployable structures/mechanisms especially during critical operations
- (Recommendation SE8) Ensure you have venting requirements
  - Verify lightweight flexible structures/blankets and composite honeycomb structures can vent rapid depressurization during ascent



# ***Tribology (Mechanisms and Lubricants) Lessons***

- (SE LL9) Most deployable structure/mechanism anomalies are due to (1) insufficient torque margins (2) non-redundancy of motion producing elements (3) snagging (4) stiction (static friction) and binding
  - Friction forces not accounted for, thermal cases ignored, design sensitive to assembly/testing, improper lubrication
- (SE LL10) Proper lubrication/coating selection
  - Ground tests failed to detect degraded lubrication because they behave differently on the ground and than in space
  - Material compatibility between lubricants and mechanisms have caused many failures
  - Lubrication migrating to unintended locations during storage/ground handling/transportation/testing/operation
  - Actual frictional characteristics of lubrication being significantly different than what was anticipated
  - Lubricants have degraded during long term storage/ground handling/transportation/testing/operation



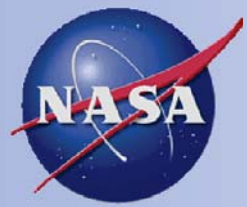
# ***Tribology Lessons***

- (SE LL11) Damage to hard coatings and lubricated surfaces
  - Micro-welding of high-load contact areas can occur when lubricating film fails on metal surfaces.
  - Vibration can break welds, producing debris/pitting preventing smooth operation of deployable structures/mechanisms
  - Occur due to excessive loading and relative vibration between two parts
- (SE LL12) Many mechanisms have been damaged when they exceeded their end of travel limits during operation
- (SE LL13) Many deployment switches not functioning properly in space
  - Switch devices will function properly in ground testing
  - Switch devices are sensitive to mounting orientation and microgravity
  - Limit switches are sensitive to thermal environment



# ***Tribology Recommendations***

- (Recommendation SE9) Add the appropriate standards to system requirements  
Examples are : NASA Space Mechanisms Handbook, NASA-STD-5017 (Mechanisms), AIAA S-114-2005 (Moving Mechanical Assemblies) and Preferred Reliability Guidelines NO. GD-ED-2209 (Spacecraft Deployable Appendage Design)
  - Redundancy should be incorporated in motion producing devices/switches
  - Maintain proper clearances between adjacent components/devices
  - Self-aligning bearings should be used (where practicable) to preclude binding due to misalignments.
  - All ferrous material bearings should employ a corrosion-resistant steel
  - Recommended typical greases used in gear trains have been Bray 600, 601, 602, 3L-38
  - Maximize utilization of rolling surfaces in mechanisms
    - Avoid slip joints
  - Use non-explosive pin pullers over pyrotechnic devices (high load carrying devices, do not eject particles and easy to incorporate redundancy)
    - Minimum retraction force margin of 100% at worst-case environmental conditions should be maintained



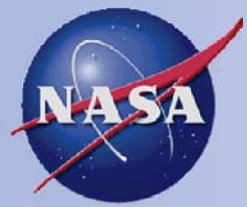
# ***Tribology Recommendations***

- (Recommendation SE10) Validate and verify the selected lubricants using NASA Space Mechanisms Handbook for guidelines
  - “Wet” grease lubrication is generally preferred over “dry” lubrication. The grease with the most heritage is good choice for many space applications
    - Such as Braycote 600 series, a synthetic-fluorinated oil-thickened grease with micron-size Teflon powder.
    - Grease has low out gassing and minimal contamination concerns for space application (temp range: -80 °C to 200 °C)
  - For extreme low temperatures and cryogenic applications, consider solid lubricants
- (Recommendation SE11) Contact stress of mating surfaces should not be great enough to cause plastic deformation and/or destroy applied coatings to prevent lubrication failure and subsequent binding/seizure
- (Recommendation SE12) Add system reliability requirements for stopping
- (Recommendation SE13) Follow NASA Space Mechanisms Handbook Mechanism and Deployed Appendage design guidelines when incorporating switches/sensors



## ***Modeling/Analysis Lessons***

- (SE LL14) Immature or inadequate modeling/analysis of environments and dynamic loading has caused many deployable structures/mechanisms failures
- (SE LL15) Deployable structures and mechanisms are often extremely difficult to accurately model/analyze, especially for large, lightweight structures



## ***Modeling/Analysis Recommendations***

- (Recommendation SE14) Develop detailed deployable structures mechanism models and analysis that are validated
  - Follow “Flight Loads Analysis as a Spacecraft Design Tool”, “Structural Stress Analysis”, “Thermal Analysis”, Reliability Practice number PD-AP-1317, 1318 and 2302, from NASA Technical Memorandum 4322A, while developing and verifying models/simulations/analysis
  - Validate models/simulations/analysis with corresponding test data where possible
  - Perform torque margin, kinematic, dynamic, clearance, structural, control, thermal and plume analysis early on and continue to model through program to confirm requirement compliance



## ***Modeling/Analysis Recommendations***

- (Recommendation SE15) When developing and validating deployable structure/mechanism models, simulations and analysis:
  - Capture realistic thermal gradients
  - Properly characterize wire harness stiffness across joints to accurately estimate resistive torques
  - Make sure effects of small forces due to friction, gravity and aerodynamic resistance have been captured



# ***Assembly and Integration Lessons***

- (SE LL16) Technical integration, communication and documentation are crucial to the build process
  - 70 to 80% of all problems encountered in assembly and integration are caused by a lack of good systems or technical integration planning
  - Many deployable structure/mechanism problems associated with workmanship errors; wiring/interconnects/solder joints and switches
- (SE LL17) Mishandling or excessive handling incidents
  - Composite structures, large flexible array panels/solar cells and thin, lightweight tethers/cables/lanyards are susceptible to ground handling damage
  - High voltage array blankets are especially susceptible to handling damage
  - Lubricants/coatings especially vulnerable to pre-launch storage mishandling
- (SE LL18) Last minute assembly and integration steps can lead to failures to deployable structures and mechanisms



# ***Assembly and Integration Recommendations***

- (Recommendation SE16) Rigorous and comprehensive assembly and integration process should be developed and followed throughout
  - Make sure loose, non-serialized materials are carefully accounted for during assembly
  - Keep accurate records of all “non-flight” installations
  - Take photos/video frequently during assembly and Integration
  - Keep hardware closed when access is not needed
- (Recommendation SE17) Establish safe handling procedures early in program
  - Procedures should be reviewed by safety personnel prior to assembly/integration
  - Deployable structures/mechanisms should be self supporting when placed in any orientation relative to gravity while in storage or deployed configuration
  - Conduct safety planning and dress rehearsals before handling
- (Recommendation SE 18) Verify final assembly operations, particularly on deployable structures and mechanisms that are single-point-failure risks
  - Pay particular attention to possible connector mismating



# ***Testing Lessons***

- (SE LL19) Flight failures due to lack of appropriate test levels and sequences in a flight environment
  - Many failures attributed to testing under non-realistic environmental conditions
- (SE LL20) Flight failures due to lack of good ground testing structures
- (SE LL21) Capturing stiffness at critical interfaces such as at deployable structure and spacecraft interface is critical to accurately predicting response during testing and verifying that flexible materials, such as wires and thermal blankets, will not jam deployable/mechanism
  - Many failures occurred due to improper characterization of wire harness stiffness across joints during ground deployment testing
- (SE LL22) Modeling is not testing, this is analysis (can be used to help testing)
- (SE LL23) Interference of ground test equipment
  - Ground test equipment, especially for large flexible structures, can mask kinematic performance and seemingly small forces providing false confidence in reliability
  - Ground test equipment can also introduce artificial constraints and forces



# ***Testing Recommendations***

- (Recommendation SE19) All tests should follow “test-as-you-fly”
  - Test in your flight environment
  - Standards need to be part of the test plan
  - Requirements should call the standards needed for compliance
- (Recommendation SE20) Have I&T leads involved with requirements development to consider designs to enhance ground tests to meet specs and environments
  - Tests need to be verifiable in 1 G test conditions
  - Tests should be done without the assistance of gravity
- (Recommendation SE21) Test the deployable structure/mechanism to the highest possible sub-system/system level
- (Recommendation SE22) Push for failure mode testing to accurately identify/verify the failure modes predicted for the deployable/mechanism
  - Verify all redundant components/modes of operation
- (Recommendation SE23) Identify ground equipment interference and compensate or eliminate
  - Ground test equipment needs to be designed to accurately simulate the effects of micro-gravity during deployment
  - Be aware of other effects that ground test equipment could have onto test hardware (artificial thermal gradients during thermal testing)

**Note: Provide sufficient resources and time to support testing**

**- First to be cut due to schedule and always under estimated**

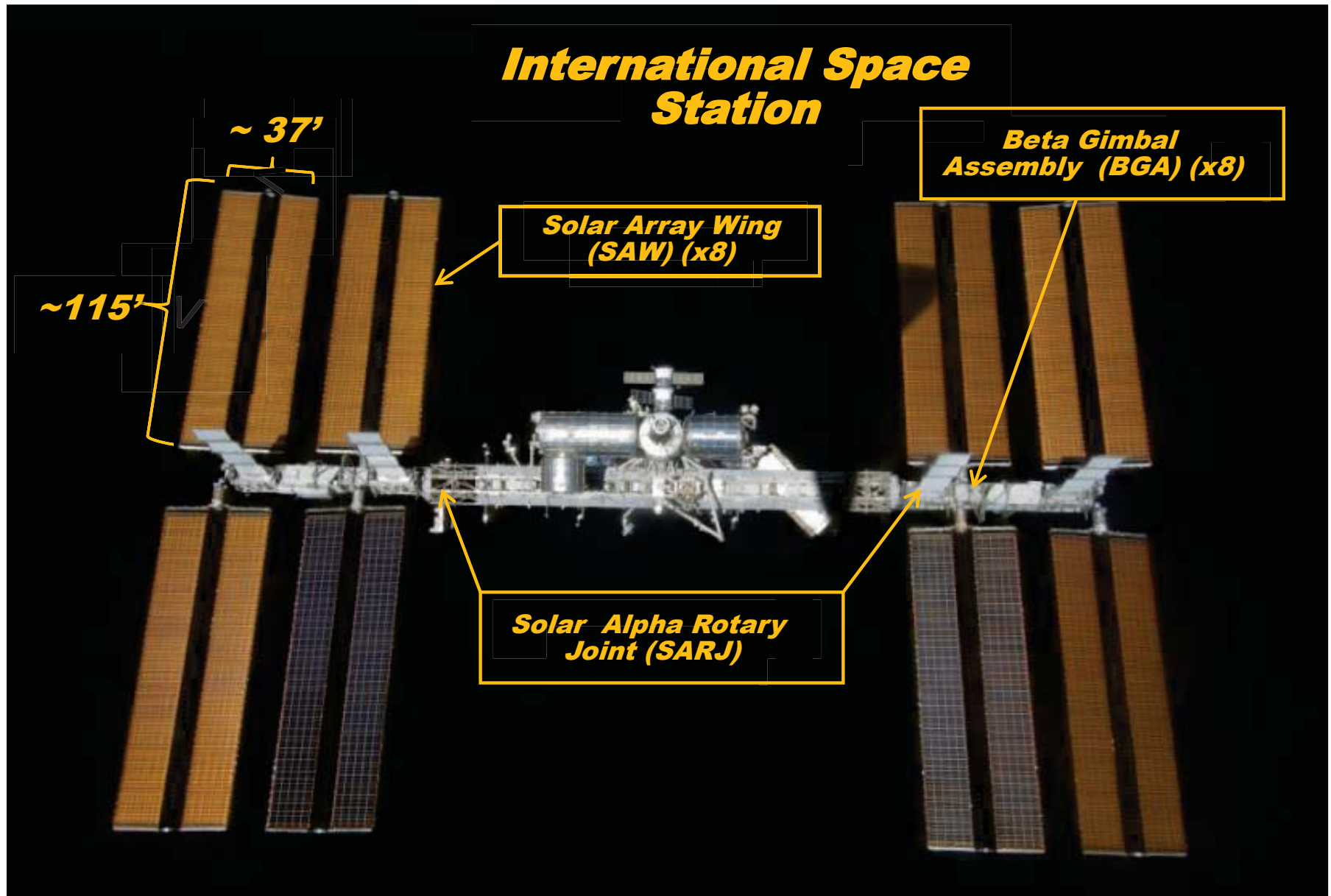


# ***International Space Station***

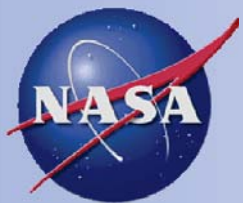
The following couple of lessons are from “Lessons Learned from ISS Solar Array Operations and Implications for Future Missions” presentation from Michael Grygier, Structural Engineering Division, NASA Johnson Space Center



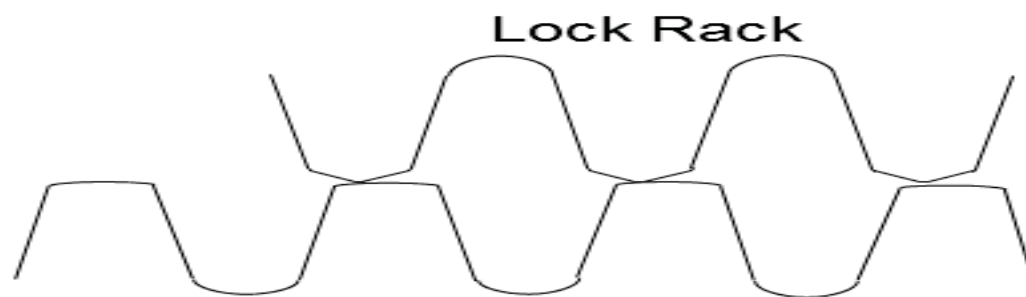
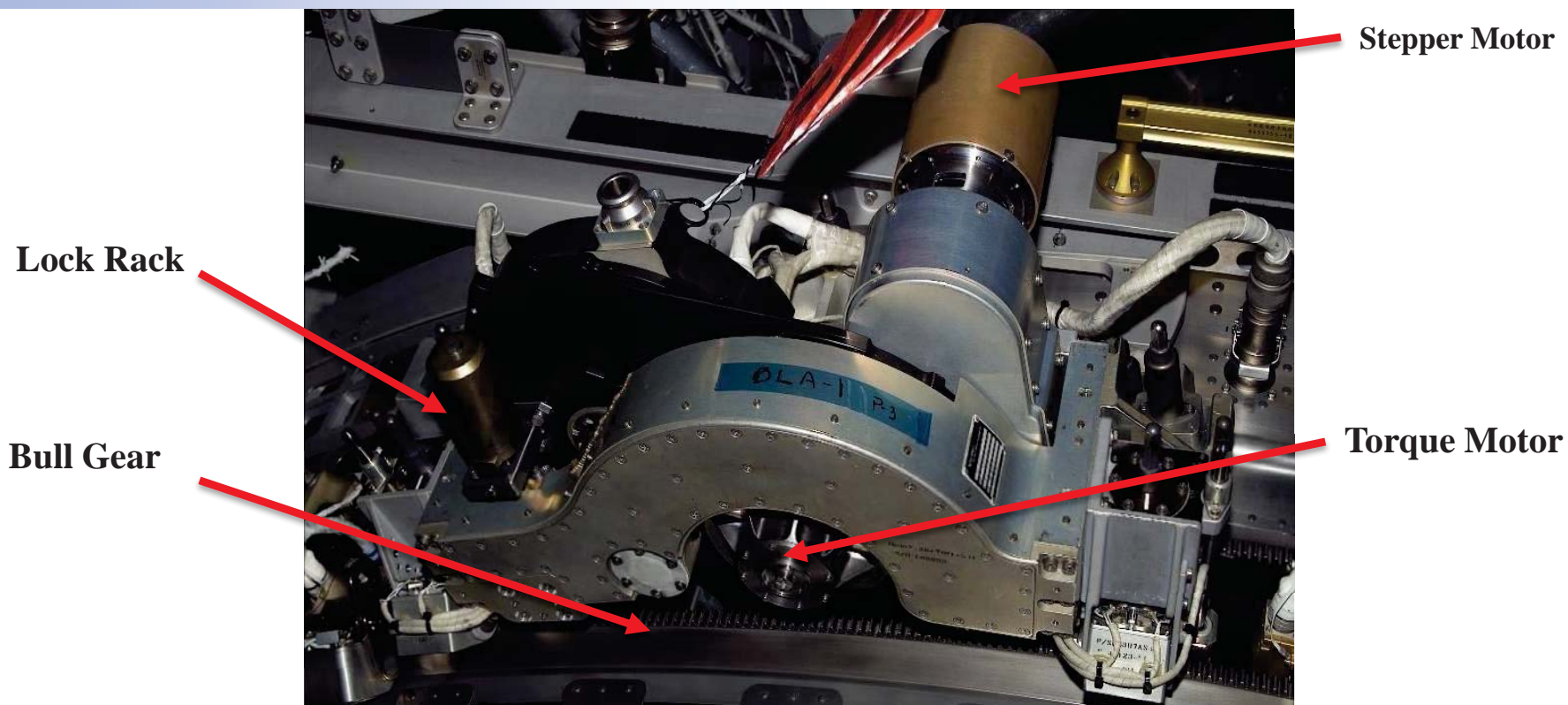
# ***ISS Solar Array Configuration***



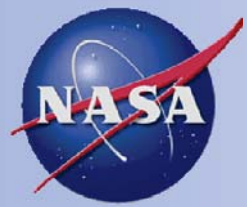
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## ***SARJ Tooth Crash***



**Toothcrash Visual**



## ***SARJ Crash Recovery***

- SARJ Toothcrash Recovery commands the SARJ in a stepper motor fashion, inducing vibrations into the entire outboard truss and solar arrays
  - This was not analyzed pre-flight.
  - Post-flight reconstructions have shown that the actual excitation and loads are fairly benign but adds 10 minutes to mission ops planning timelines



# ***Shadowing***

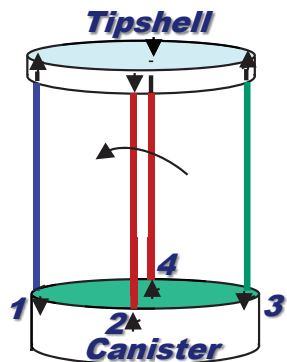
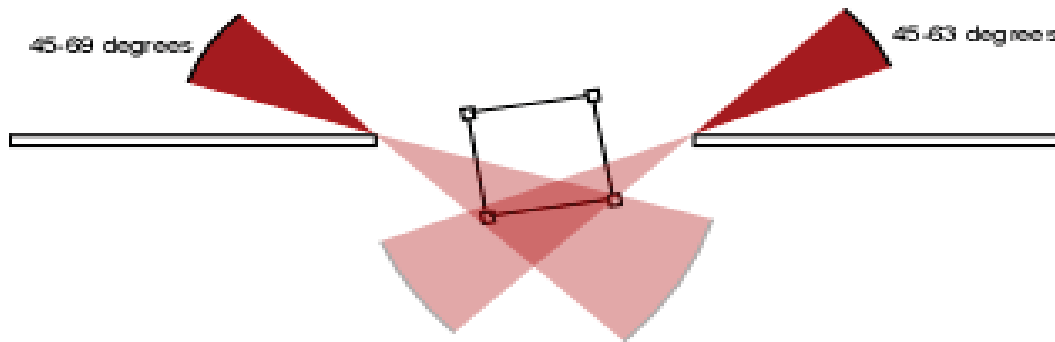




# Shadowing

Shadowing of a single longeron can cause a catastrophic hazard

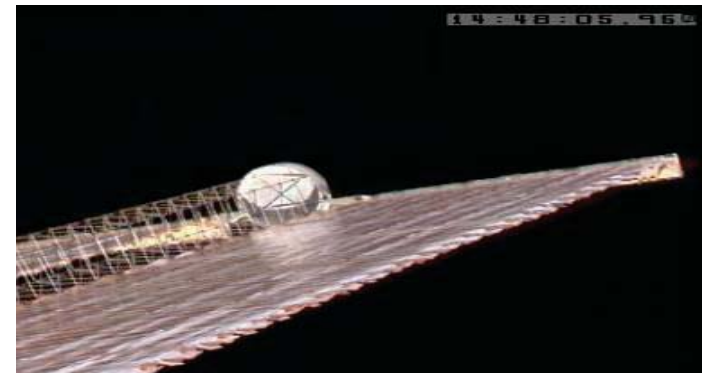
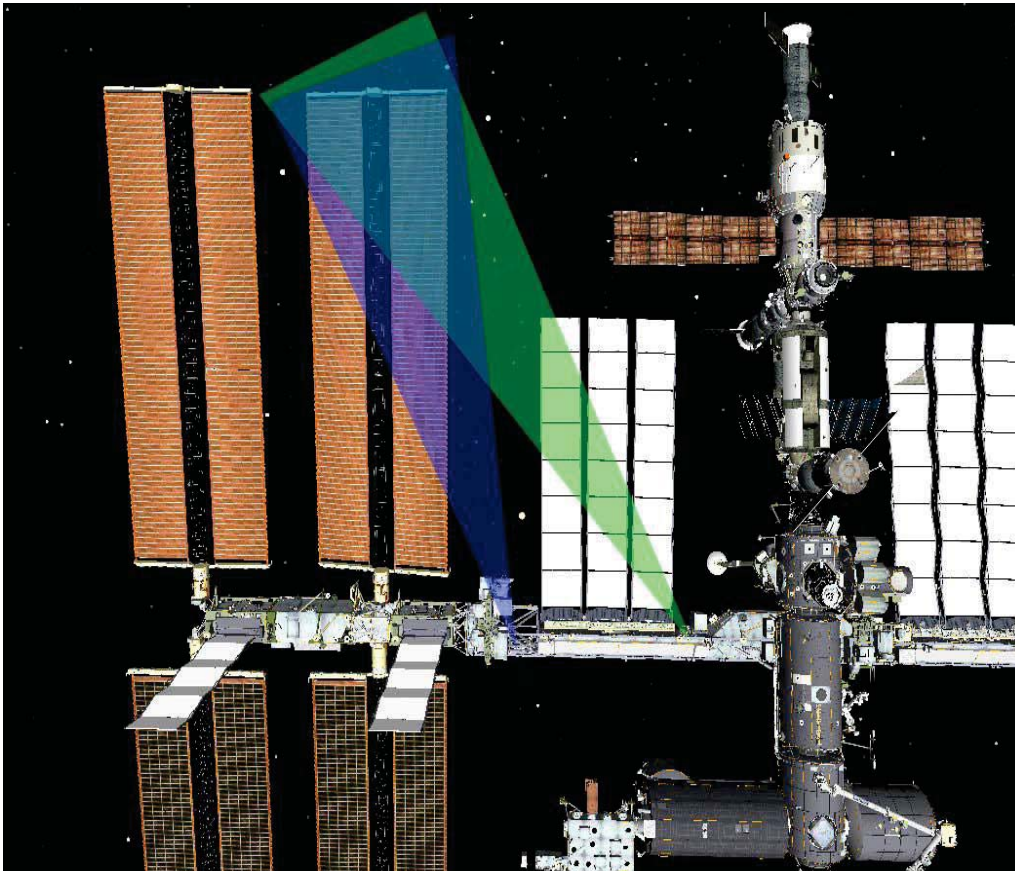
- Thermal structural loads build over time
- Loads can exceed mast buckling limit in ~30 minutes



- Shadow on longeron #1 causes it to be cooler than the other three
- Due to all four longerons being attached to the same relatively rigid plane, a loading condition is established
- #1 pulls the tipshell toward the canister
- Causing 2 and 4 to go into compression and 3 in tension
- The compression load can lead to a buckling failure



## ***Thruster Effects***



**Two truss cameras capture 3-D Solar Array tip motion while excited by thruster firings**



## ***Recommendations***

- Solar array wing/motor controller systems need to be analyzed dynamically with the flex model included to verify loads in the solar arrays are acceptable for nominal as well as contingency operations
- Preventive shadowing should be incorporated as part of solar array wing designs
- Do not underestimate the different operational scenarios requiring the solar array position to be controlled to some other position than the optimal power-generating position: Plume Loads, Mechanical Loads, Thermal Loads, Erosion/Contamination, Vehicle maneuvers
  - Don't place arrays near attitude control thrusters
- Mast structures should have adequate margins that will sufficient structural integrity even after some damage is sustained



# ***Hubble Telescope***

- From a Space Telescope Feasibility Study showing a requirement violation
- Result: the small-diameter bi-STEM booms buckled in space
- Always validate and verify your requirements

## **2.2.2.2 Deployed Dynamics:**

A preliminary appraisal of the dynamic behaviour of the deployed Concept 1B paddle shows that the natural fundamental frequency of the structure is about 0.3 Hz which violates the requirement to be below 0.2 Hz. The blanket fundamental mode is about 0.7 Hz.

The paddle frequency cannot be lowered by reducing the stiffness of the BiSTEM element since the next size down (21.9 mm) has insufficient flexural stiffness to remain stable under the compressive loading due to blanket tension.

As with Concept 1A, it is also considered that interference with the pitch and yaw control of the Telescope could be a problem and that the dynamics are complex to analyse. (See Figure 7).



# ***Requirement Considerations***

**Requirements are all about *communication, communication, communication!***

- Avoid multi- requirement statements
  - Use single concise requirement statements
  - Include rationales for rustication, history, and further clarification
- Assign requirement ownership and accountability
  - They will track, monitor and verify compliance
- All requirements should have traceability and requirement flow down
- System requirements should reflect the entire life cycle
- The LaRC LMS-CP-5526 (Product Requirements Development and Management Procedures) is a quick and excellent guide to requirements management and development (call me, I can email you a copy)



## ***Requirement Definition***

- Develop an end-to-end concept of operations to fully understand your operating environment
- Develop a complete system architecture based on the concept of operations
- Define your system requirements based on the concept of operations and science and program requirements



## ***Interfaces a Special Consideration***

- Ensure interfaces between organizations are worked out in detail, agreed to by both sides and documented
  - Assign a dedicated and accountable engineer to assure the hardware being built matches the Interface Control Documents (ICDs)
  - Ensure cognizant engineers verify consistency between their hardware and the ICDs/ drawings, and provide proper notification of interface changes
  - Use vendor ICDs where applicable
  - Do not maintain two sets of ICDs
- Recognize the importance of contamination-control engineering during every phase of hardware design and development
  - Establish quantitative cleanliness requirements to control particulate and molecular contamination
- Proper installation and assembly should be verifiable and easily inspected
  - If not have good photos and video

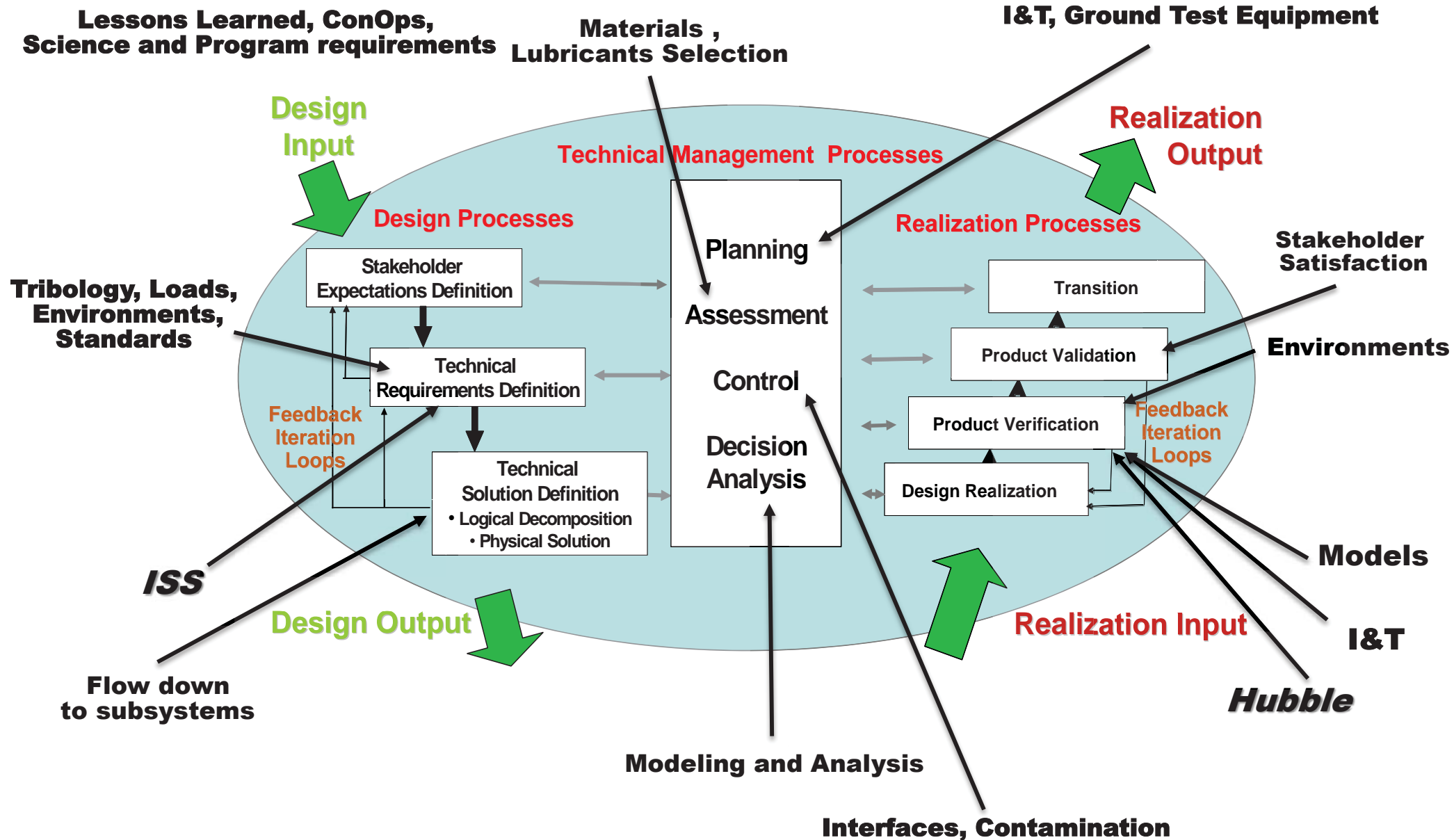


## ***Some Standard and Guideline Recommendations***

- General recommendation: Use the following when developing system engineering processes for deployable structures/mechanisms:
  - NPR 7123.1B (NASA Systems Engineering, SE Processes and Requirements),
  - NASA/SP-2007-6105 (SE Handbook)
  - Then develop and implement a Systems Engineering Management Plan
- General recommendation: In addition, the following documents contain good standards, guidelines, and processes:
  - CxP 70135 Structural Design and Verification Document,
  - NASA-STD-5017 Space Mechanisms,
  - NASA-STD-5019 MSFC-RQMT-3479 Fracture Control,
  - AIAA S-114-2005 Moving Mechanical Assemblies and Preferred Reliability Guidelines NO. GD-ED-2209
  - GT-TE-2403 Spacecraft Deployable Appendage Design and Test Guidelines



# Applying Technical Management Processes





# ***Key Solar Array Structures Requirements***

- The following are key requirements associated with Solar Array Structures:
  - Packing efficiency
  - Mass
  - Reliability
  - Structural (Thermal-Mechanical) Stability
  - Pointing and Control
  - Solar Array Specific Power
  - Solar Array Stowed Power
  - Scalability
  - Feasibility
  - Cost
- Essential to have a mission scenario and design reference mission defined



## ***Summary***

- Numerous lessons learned from deployable structures and mechanism failures across multiple NASA agencies/industry/DOD have been summarized in this presentation
  - The purpose is to increase awareness of previous failures so we don't repeat past mistakes
  - And to help develop guidelines/requirements for development of future NASA deployable structures and mechanisms
- Currently these lessons learned are being applied and assessed against Solar Array Structures (SAS) involved with NASA Research Announcements for solar array research and development
  - Supports requirement development process, evaluation of solar array designs and support development/evaluation of test plan for solar arrays/mechanisms
  - Continue SAS lessons learned updates and presentations



## ***References***

1. Pascal Lecointe, Space Risks Underwriter, Space Power Workshop, 2005, Original source of information: Frost and Sullivan and Airclaims
2. Geoffrey A. Landis<sup>1</sup>, Sheila G. Bailey<sup>1</sup>, and Renee Tischler<sup>2</sup>, “Causes of Power-related Satellite Failure”,
3. Michael T. Freeman, Electromagnetic Sciences, Inc. “Spacecraft On-Orbit Deployment Anomalies: What Can Be Done?”